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M. Brüggen, E. Roediger

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# Simulating Galaxies in Clusters

Marcus Brüggen and Elke Roediger

Jacobs University Bremen  
Campus Ring 7, 28759 Bremen, Germany  
*E-mail:* {m.brueggen, e.roediger}@jacobs-university.de

How galaxies form has puzzled astrophysics for decades and is among the key questions in contemporary astrophysics. Clusters of galaxies are good laboratories for the study of galaxy evolution. Among the processes that affect the life of a galaxy are the headwinds that the galaxies experience as they fly through the hot and dilute intracluster medium and the energetic outbursts from the supermassive black holes that sit in the centre of galaxies. Using the JUMP supercomputer, we have simulated these processes using adaptive-mesh hydrodynamical simulations.

## 1 Introduction

Galaxies are the building blocks of the universe. They are composed of stars, the interstellar medium (ISM) and dark matter halos. They show a variety of morphologies, ranging from ellipticals over spirals to irregulars, from dwarfs to giants. The galaxies themselves are part of still larger structures, they are members of groups and clusters of galaxies. A few galaxies are also isolated. It is a well-established fact that the evolution of galaxies is influenced by their environment. Moreover, the growth of galaxies is believed to be strongly determined by the supermassive black hole that resides in the centre of every galaxy, which we will discuss in Sec. 4.

Especially the properties of disk galaxies change with environment: In denser regions, the galaxies tend to contain less neutral gas, show a weaker star formation activity and redder colours than galaxies in sparse regions (e.g. Van Gorkom (2004)<sup>19</sup>, Goto (2003)<sup>3</sup>). Several processes have been proposed to explain these features. One of the most important processes is ram pressure stripping (RPS) which works as follows: Besides galaxies, clusters also contain a large amount of rarefied gas – the intra-cluster medium (ICM). In fact, there is more mass in this dilute intra-cluster gas than in all the stars of the cluster galaxies. As galaxies move through a cluster, they also move through the ICM. The ram pressure caused by these motions can push out (parts of) their gas disks.

A galaxy's gas is its raw material for star formation, therefore such ram pressure stripping has severe consequences. E.g. the characteristic blue colour of spiral galaxies is due to shortlived massive stars. When the star formation is reduced because the galaxy has lost its gas and no new stars are formed, the galaxy's colour changes from blue to red. So the process of RPS seems to be a good candidate to explain several of the differences between galaxies in different environments.

Moreover, several individual galaxies are known to show characteristics of RPS, i.e. an undisturbed stellar disk but a distorted and truncated gaseous disk (e.g. NGC 4522<sup>5-7</sup>, NGC 4548<sup>20</sup>). Recently, observations of tails of stripped gas<sup>9,18</sup> have been presented. They reveal long (up to 100 kpc) and narrow (10-20 kpc) gas tails that stretch away to one side of the galaxy. The structure of these tails differs from flaring, S-shaped to very narrow and nearly structureless. These observations provide an excellent opportunity to compare

to simulations and thus understand RPS in more detail. The stripped gas plays an important role in the chemical evolution of the ICM. Practically all metals (in astrophysics this means all elements heavier than hydrogen and helium) are produced in stars inside galaxies. Hence, the metals found in the ICM must originate from the cluster galaxies. Obviously, galactic gas lost by ram pressure stripping is a metal source for the ICM. Hydrodynamical simulations of the cluster crossing of a disk galaxy, i.e. where the galaxy is exposed to a varying ram pressure, had not been performed so far. All hydrodynamical simulations up to now<sup>10, 17, 16, 13, 14</sup> used a constant ram pressure. Additionally, the work of Schulz (2001)<sup>17</sup>, Roediger (2005)<sup>16</sup>, Roediger (2005)<sup>13</sup> has shown that the gas removal from the galactic potential does not happen instantaneously, but that it takes some time until the gas is accelerated enough to be unbound from the galaxy's potential. Thus, in cases of short ram pressure peaks, this time delay may play an important role. We have performed simulations where the galaxy is exposed to a varying ram pressure.

## 2 Method

We performed our simulations in three dimensions in Cartesian geometry using a modified version of the adaptive mesh refinement code FLASH (version 2.5). The FLASH code was developed by the Department of Energy-supported ASCI/Alliance Center for Astrophysical Thermonuclear Flashes at the University of Chicago. FLASH is a modular block-structured AMR code, parallelised using the Message Passing Interface (MPI) library. It solves the Riemann problem on a Cartesian grid using the Piecewise-Parabolic Method (PPM). More details can be found under <http://flash.uchicago.edu>.

We chose a simulation box large enough to contain a substantial part of a whole galaxy cluster. The model galaxy is moving on a realistic orbit through the cluster, i.e. it is moving through the grid. Here, not only the strength of the ICM wind varies, but also its direction. For demonstration, Fig. 1 displays a slice through the simulation grid in the orbital plane of the galaxy.

The galaxy's orbit is marked by the black line. The position and size of the third frame (lhs column) in Fig. 2 is marked by the white rectangle. The initial diameter of the galaxy is about half the size of the white rectangle. Our model galaxy is a massive disk galaxy with a flat rotation curve at  $200 \text{ km s}^{-1}$ . We studied different galaxy orbits in different clusters. The simulations need to cover an enormous range of scales (compare Figs. 1 and 2): The simulation box has to contain the whole orbit of the galaxy, which requires a box size of  $(-1 \text{ Mpc}, 1 \text{ Mpc}) \times (-2 \text{ Mpc}, 2 \text{ Mpc}) \times (-1 \text{ Mpc}, 1 \text{ Mpc})$ . On the other hand, the dynamics inside and close to the galaxy have to be resolved. At minimum, a resolution of  $0.5 \text{ kpc}$  is needed near the galaxy. Formally, this results in an effective resolution of  $4096 \times 8192 \times 4096$  grid cells. Thanks to the adaptive mesh of the FLASH code and the supercomputers at the FZ Juelich, this is possible. A complete cluster crossing requires a physical runtime of 3 Gyr. The typical runtime for these simulations is 2000-3000 CPUh, each run needs 40 GB of disk space and 30-40 GB memory. We are also running one simulation where the resolution is a factor of two better, which takes approximately 20 000 CPUh.

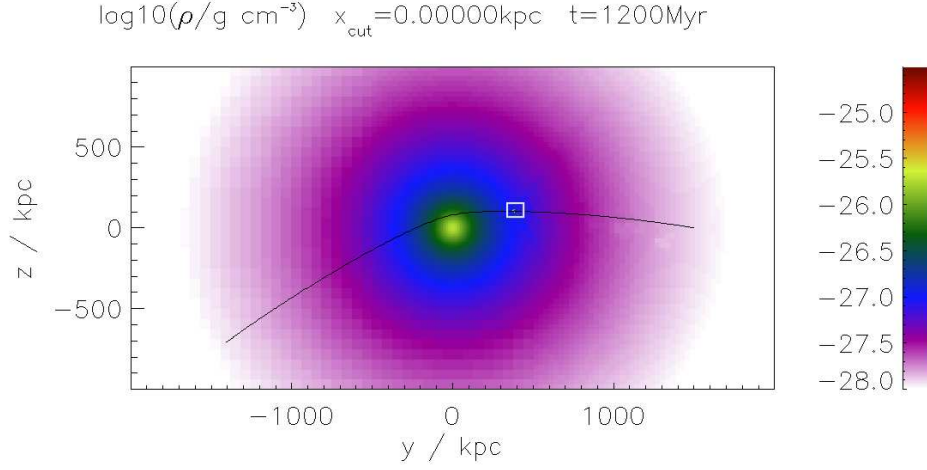


Figure 1. Density in the orbital plane of the galaxy. The orbit of the galaxy is shown by the black line. The white rectangle marks the position of the third frame in the left column in Fig. 2.

### 3 Results

As an example, Fig. 2 shows a series of snapshots of the density in the orbital plane of the galaxy. In the left column, just the vicinity of the galaxy is shown (compare to Fig. 1). The right column shows the distribution of stripped gas along the galaxy's orbit. A movie can be found here<sup>a</sup>. First, the galaxy moves subsonically, then it becomes supersonic. The gas disk becomes smaller and smaller as the galaxy is ram pressure stripped. In the last timestep shown the galaxy is already stripped completely, the peak in density is not located at the galactic centre anymore. The stripped gas is distributed all along the orbit.

There are several different aspects that can be investigated with these simulations:

#### 3.1 Comparison to the Analytical Estimate

Ram pressure stripping is not only important for the stripped galaxies, but also for the ICM in the galaxy cluster. The galactic gas is enriched with heavier elements (“metals” in astrophysical terminology), and as the galaxies lose their gas, also the metals are distributed through the cluster. Simulations that aim at modelling the enrichment history of the ICM have to model the evolution of a whole galaxy cluster, including ICM, dark matter, and galaxies. This alone is computationally expensive, thus, they rely on analytical approximations for the single enrichment processes. For RPS, the analytical estimate explained below is commonly used.

The usual way to estimate the amount of gas loss for galaxies moving face-on follows the suggestion of Gunn&Gott (1972)<sup>4</sup>. Here, one compares the gravitational restoring force

<sup>a</sup>[http://www.faculty.iu-bremen.de/eroediger/PLOTS/RPS\\_CLUSTER/dens.metdens.movie\\_x0.mpg](http://www.faculty.iu-bremen.de/eroediger/PLOTS/RPS_CLUSTER/dens.metdens.movie_x0.mpg)

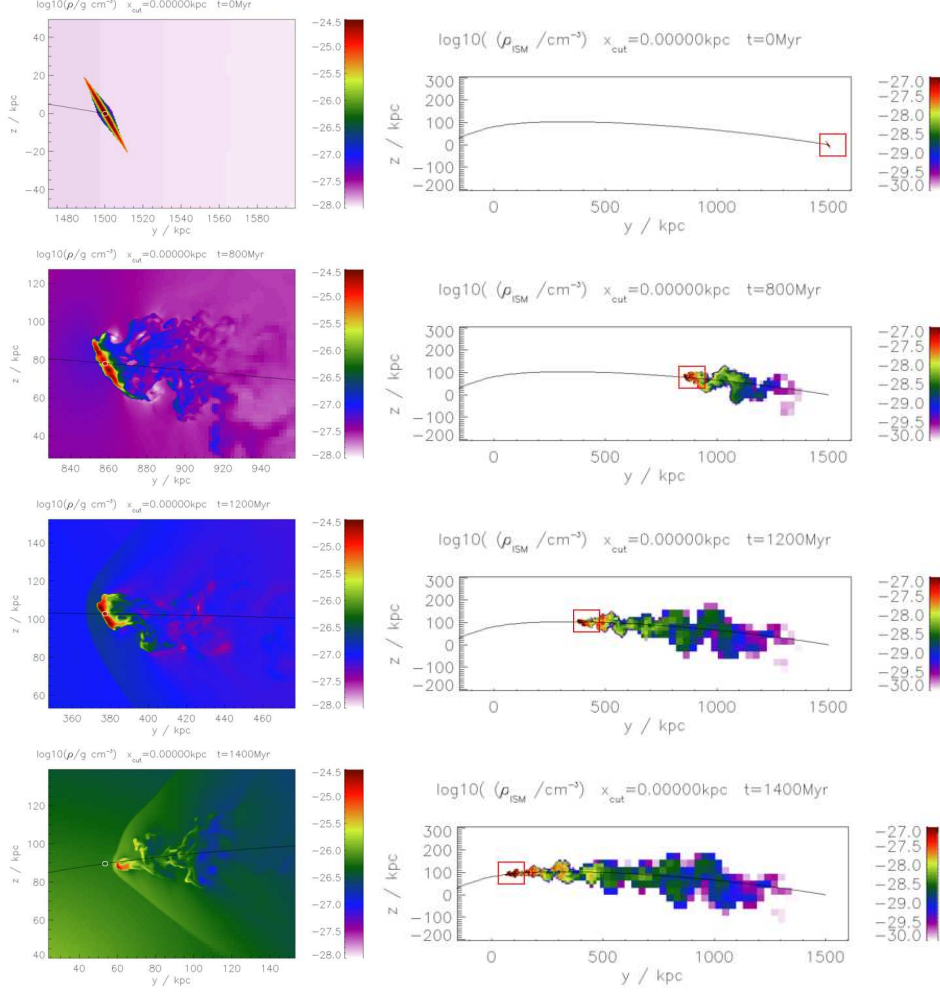


Figure 2. Time series of snapshots of a simulation run: The left column shows the gas density in the orbital plane. The small white circle marks the position of the galactic centre. In the second frame the galaxy moves still subsonic, then it becomes supersonic as indicated by the bow shock. In the last frame, the galaxy is already stripped completely. The frames in the right column show the density of the *galactic* gas only, i.e. they demonstrate the distribution of the stripped gas.

In all frames, the black line marks the galaxy's orbit. The frames in the left column show a much smaller part of the simulation grid. For orientation, the position and size of the lhs frames is marked by red rectangles in the rhs frames. However, even the frames in the right column do not show the complete simulation box (compare to Fig. 1).

per unit area and the ram pressure for each radius of the galaxy. At radii where the restoring force is larger, the gas can be retained, at radii where the ram pressure is larger, the gas will be stripped. The transition radius is called the stripping radius. Simulations with constant ram pressure generally found a good agreement between the analytical estimate and the

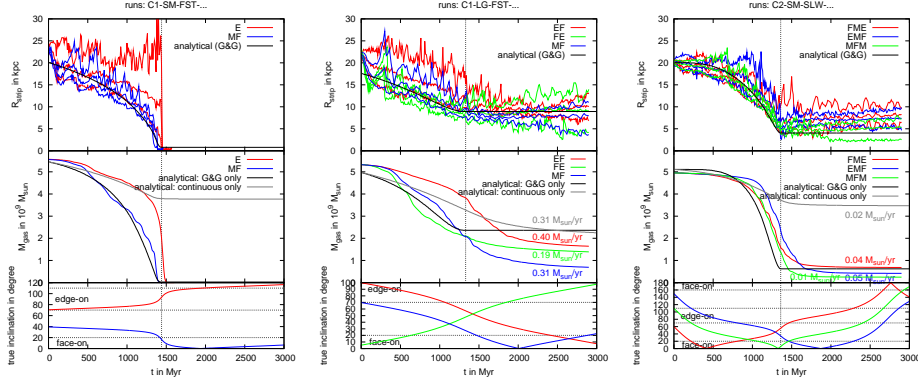


Figure 3. Comparison between analytical and numerical stripping radius (top panels) and bound gas mass (middle panels). The bottom panels display the evolution of the true inclination, i.e. the angle between the galaxy’s rotation axis and the direction of motion. Each column is for one orbit (see title of column), different inclinations are colour-coded (see legend).

For the numerical stripping radius, the mean value (thick lines) as well as maximum and minimum radius (thin lines) as described in Roediger et al. (2006)<sup>13</sup> are shown.

Analytical estimates according to the Gunn&Gott criterion are shown as black lines for the stripping radius as well as for the remaining gas mass. For an explanation of continuous stripping see Roediger et al. (2006)<sup>13</sup> and Roediger & Brüggen (2007)<sup>11</sup>.

simulated gas disk radius and mass. Although this estimate is derived for face-on galaxies, it holds well as long as the galaxy is not moving close to edge-on<sup>13</sup>. An aspect not captured by the analytical estimate is the delay in gas loss. Even if the ram pressure is large enough to remove some part from the galaxy, it takes some time until the gas is accelerated to the escape velocity.

In order to apply this estimate to our simulations, we use a time-dependent version of the classical Gunn&Gott criterion, i.e. for each timestep we compare the gravitational restoring force to the current ram pressure.

Figure 3 compares analytical estimates and numerical results for the stripping radius and the remaining gas mass for different runs. Each column is for one orbit, inside each column, different inclinations are colour-coded.

The analytical estimate is shown as black lines. This estimate neglects several aspects, e.g. inclination, a possible evolution of the galaxy (e.g. decrease in gas surface density) and the fact that the gas loss does not happen immediately, but with a certain delay. Despite these shortcomings, the analytical and numerical result for the stripping radius agree remarkably well. The only exception occurs on an orbit characterised by a narrow ram pressure peak of medium amplitude (rhs column of Fig. 3, the galaxy is expected to be stripped severely, but not completely), and here only during the ram pressure peak. If the galaxy moves face-on during the ram pressure peak, it is stripped completely, although the analytical estimate predicts a stripping radius of 4 kpc. If the galaxy moves with medium inclination through the cluster centre, it can retain a larger disk than predicted. However, also for this orbit, during the first Gyr of these simulations, the agreement between analytical estimate and numerical results is good. The differences are found only during the ram pressure peak. For the galaxies with medium inclination, this behaviour is caused by the delay of the gas loss combined with the shortness of the ram pressure peak.

### 3.2 Distribution of Stripped Gas Along the Orbit:

The rhs column of Fig. 2 demonstrates that the galaxy is losing gas continuously all along the orbit. The knowledge about where exactly the galaxy deposits which amount of stripped gas is crucial for the investigation of the metal enrichment history of the ICM. An analytical estimate for the ISM distribution along the orbit can be derived from the analytical estimate of the stripping radius explained in Sect. 3.1. According to this estimate, the galaxy does not lose any gas after pericentre passage, all stripped gas should be deposited before the pericentre. However, the simulations show that the galaxy loses gas after pericentre passage, and the galaxy loses gas more slowly than predicted. Thus, the stripped gas is spread much wider along the orbit. Details of the distribution depend also strongly on inclination.

## 4 Feedback by Active Galactic Nuclei

Recent observations of galaxy clusters show a multitude of physical effects that occur when powerful jets launched by supermassive black holes interact with the surrounding medium (See Brüggen & Kaiser 2002<sup>1</sup>). While these effects are widely believed to be crucial for the formation of structure in the universe, they are still poorly understood. Clusters of galaxies are excellent laboratories for studying the interaction between active galactic nuclei (AGN) and diffuse gas. Recent observational evidence demonstrates that the lives of AGN and their environment are closely intertwined. This complex pattern of processes has been simulated with unprecedented realism by our group at the Jacobs University Bremen using the JUMP supercomputer.

Again we used a modified version of the adaptive-mesh hydrodynamics code FLASH described above for these simulations. It uses a criterion based on the dimensionless second derivative of a fluid variable to refine or derefine the grid. Collisionless matter, i.e. stars and dark matter, were represented by particles that interact gravitationally with each other and the gas. Our initial models were extracted from cosmological smoothed-particle hydrodynamics simulations and typically included around 700,000 dark matter and star particles. We modified the FLASH code to follow the central black hole and modelled the jet as inflow boundary conditions that lie within the computational domain. Moreover, we developed a fast multigrid gravity solver in order to be able to simulate the galaxy cluster for more than 300 million years.

We have achieved the following:

- We have studied the interaction of the jet with its environment, for the first time taking into account the dynamic nature of the cluster gas. The simulations successfully reproduce the observed morphologies of radio sources in clusters. We find that cluster inhomogeneities and large-scale flows have significant impact on the morphology of the radio source.
- The ICM has a metallicity of about 1/3 solar. However, cooling core clusters, i.e. clusters with a centrally peaked X-ray brightness, show peaked abundance profiles. A number of observations indicates that supernovae in the central galaxy are mainly responsible for the metal enrichment in the central part of clusters. However, the



observed metallicity profiles are much broader than the light profiles of the central cluster galaxy. Hence, the difference in the light and the metal distributions are interpreted as the result of transport processes that have mixed metals into the ICM. While it appears to be established that the metals produced by the central galaxy are dispersed into the ICM to form the broad abundance peaks, it remains unclear what the mechanism is via which the metals are transported. As one likely mechanism, we studied the effect of AGN-inflated bubbles that rise buoyantly and lift metal-rich gas upwards. We demonstrated that AGN can account for the distribution of metals in clusters of galaxies (for more details see Roediger et al. (2007)<sup>12</sup>)

- Using realistic 3D simulations of jets in a galaxy cluster, we address the question what fraction of AGN energy is dissipated in shocks. We find that weak shocks that encompass the AGN have Mach numbers of 1.1-1.2 and dissipate at least 2 per cent of the mechanical luminosity of the AGN. In most cases this is sufficient to balance the radiative losses of the gas. In a realistic cluster medium, even a continuous jet can lead to multiple shock structures, which may lead to an overestimate of the AGN duty cycles inferred from the spatial distribution of waves. (for more details see Brügggen et al. (2007)<sup>2</sup>)

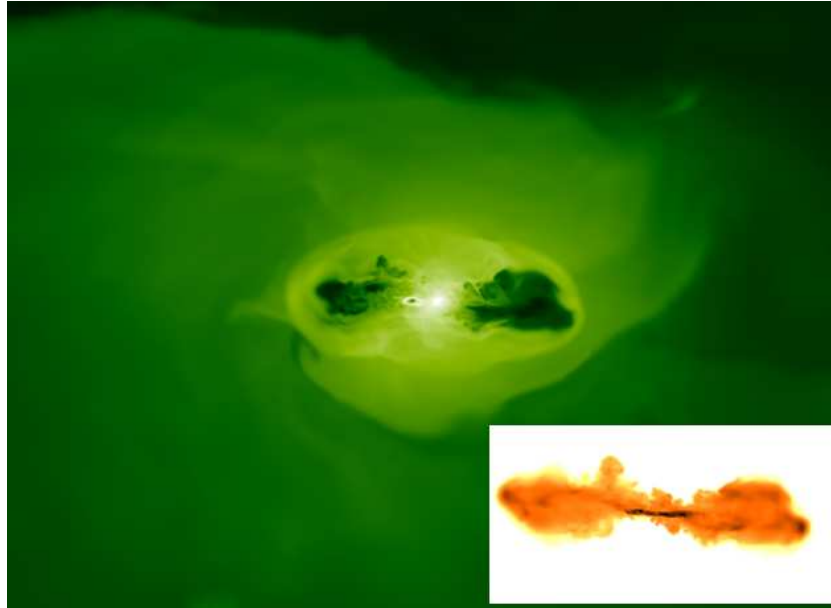


Figure 4. Snapshots of the gas density in a simulation of a jet in a cluster of galaxies. One can see how the jet drives shocks into the intracluster medium. The inset shows the simulated radio emission from this jet. The shock surrounding the two cavities are also clearly visible.



## 5 Concluding Remarks

The simulation of the complex multi-physics and multi-scale processes in galaxies is just at its beginning. It is a formidable computational challenge that will continue to drive the requirements for supercomputing infrastructure. Here we have presented some recent successes using grid-based simulations on adaptive meshes.

## Acknowledgments

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